Advanced Environmental Barrier Coating Development for SiC/SiC Ceramic Matrix Composite Turbine Vane Components

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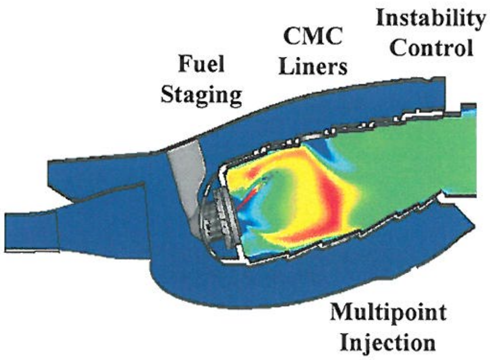
Outline

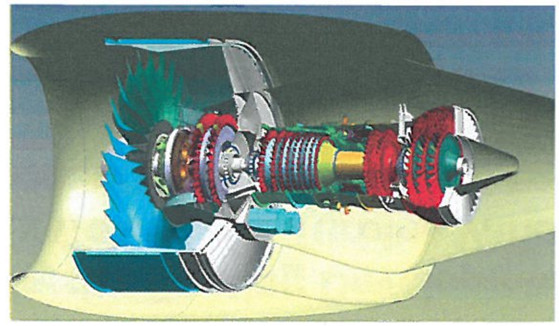
- **Turbine environmental barrier coating system development: needs and challenges**
- **Advanced environmental barrier coating systems for CMC turbine airfoils**
  - NASA coating development approaches
  - Current development status
- **Development of SiC/SiC ceramic matrix composite turbine vane environmental barrier coatings and advanced testing**
  - Environmental barrier coating processing
  - Advanced CMC-EBC rig testing developments
  - Subelement and subcomponent demonstrations in high pressure burner rig
- **Summary and Conclusions**

NASA Environmental Barrier Coating (EBC) - Ceramic Matrix Composite (CMC) Development Needs

- **NASA Fundamental Aeronautics Program (FAP)**: Next generation high pressure turbine airfoil environmental barrier coatings with advanced CMCs
  - N+3 generation (2020-2025) with advanced 2700°F CMCs/2700-3000°F EBCs (uncooled/cooled)
- **NASA Environmentally Responsible Aviation (ERA) Program**: Advanced environmental barrier coatings for SiC/SiC CMC combustor and turbine vane components, technology demonstrations in engine tests
  - N+2 generation (2020-2025) with 2400°F CMCs/2700°F EBCs (cooled)



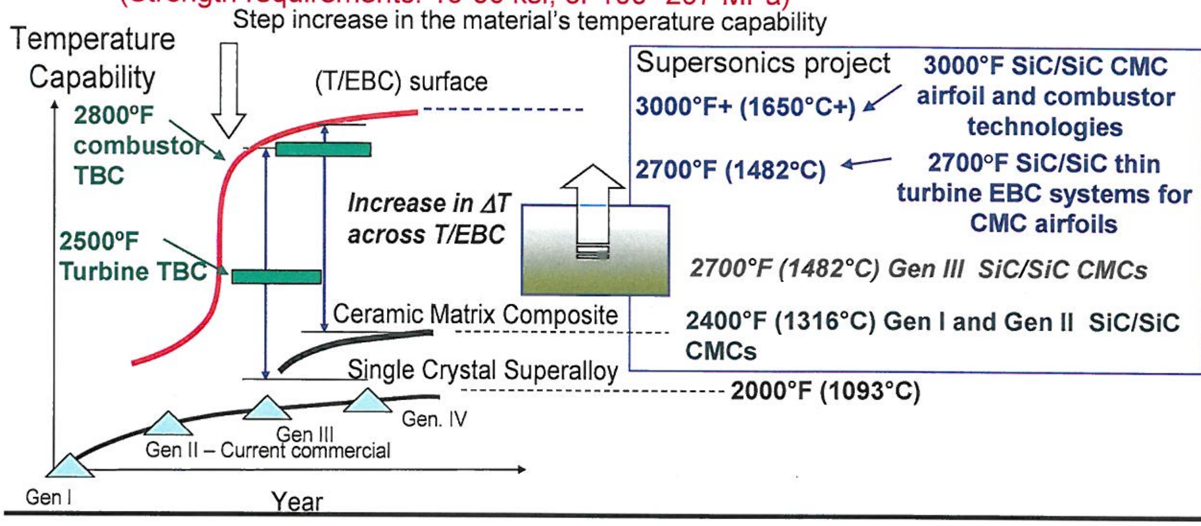
Low emission combustor



High Pressure Turbine CMC vane and blade

NASA EBC and CMC System Development

- Emphasize temperature capability, performance and *long-term* durability
- Develop innovative coating technologies and life prediction approaches
- Establish fundamental understanding of materials behavior
- Meet long-term subsonic engine hot-time life requirements
  - Recession: <5 mg/cm^2 per 1000 h
- Highly loaded EBC-CMCs capable of thermal and mechanical (static/low cycle and dynamic) loading
  - (Strength requirements: 15-30 ksi, or 100- 207 MPa)



NASA Turbine Environmental Barrier Coating Development Emphasis

- **Improve temperature capability, water vapor stability and long-term durability for advanced high pressure, high bypass turbine engines**
- **Improve coating strength and toughness**
  - Resistance to high-heat-flux, engine high pressure, combustion environment, creep-fatigue, loading interactions
- **Improved erosion, impact and calcium-magnesium-alumino-silicate (CMAS) resistance and interface stability**
- **Develop and mature advanced processing for turbine airfoil EBCs**

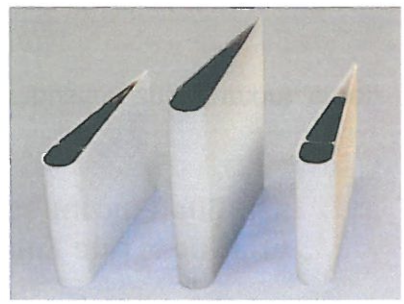
NASA ERA EBC Development Objectives and Approaches

OBJECTIVE

- Develop a 2700°F turbine EBC systems for advanced, 2400°F capable, high strength SiC/SiC CMC system with 1000 hr durability goals
- Develop advanced vapor based turbine environmental coating processing
- Demonstrate high thermal gradient, heat flux, and mechanical loading capabilities of coated CMC systems - addressing LE, TE, cooling hole, and substructure issues
- Establish EBC-CMC airfoil property database and life prediction models
- Demonstrate HPT CMC turbine vane viability and durability in the High Pressure Burner Rig environments

APPROACH

- Addressing component processing technologies for multicomponent turbine airfoil coating systems
- Developed simulated engine thermal gradient biaxial strength, fatigue and rupture testing to improve turbine vane EBC and CMC processing and design confidence
- Demonstrate turbine airfoil EBC-CMC systems for rig durability and performance testing



Environmental barrier coating coated SiC/SiC CMC vanes

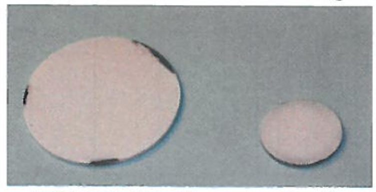
NASA Turbine Vane EBC for ERA Program Demonstrations

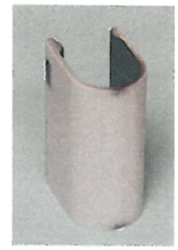
- Focus on high technology readiness level (TRL), high stability multicomponent HfO_2-RE_2O_3-SiO_2/$RE_2Si_{2-x}O_{7-2x}$ environmental barrier and advanced HfO_2-Si bond coat developments
- Processing optimization for improve coating density and composition control robustness
- Develop advanced NASA high toughness, Alternating Composition Layered Coating (ACLC) compositions and processing for low RE t' low rare earth dopant low k HfO2 and higher rare earth dopant silicates
- Optimize HfO_2-Si based series bond coats

  - Achieving high toughness has been one of key emphases for NASA coating technologies

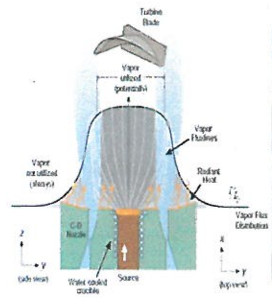
Development and Processing of *Directed Vapor* Electron Beam - Physical Vapor Deposition (EB-PVD)

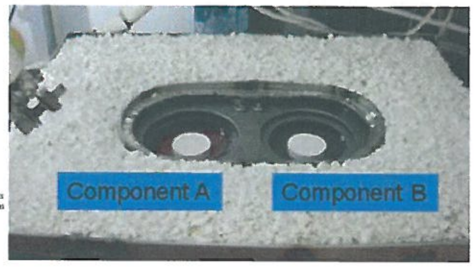
- NASA programs in supporting processing developments and improvements with Directed Vapor Technologies International, Inc.
  - Multicomponent thermal and environmental barrier coating vapor processing developments
  - High toughness erosion resistant turbine coatings
  - Affordable manufacture of environmental barrier coatings

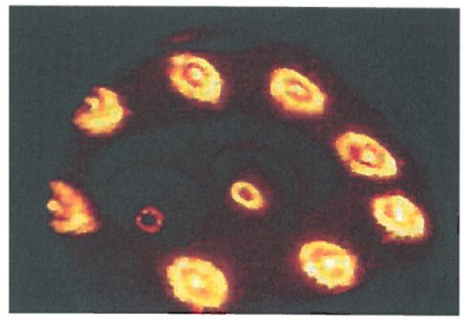




Advanced multi-component and multilayer turbine EBC systems



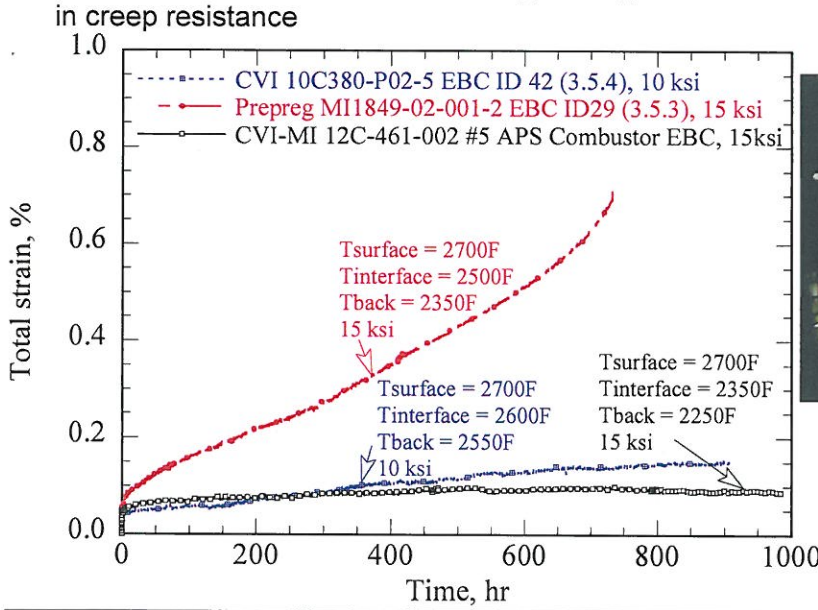


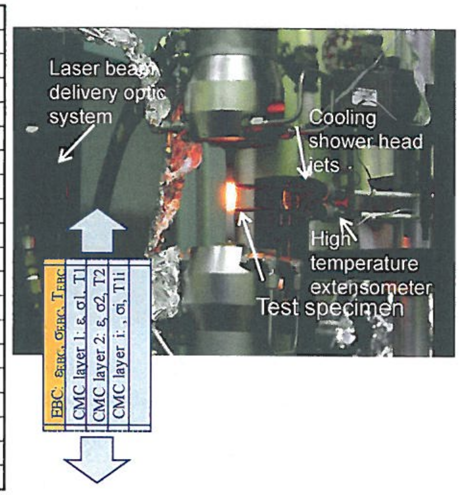


Directed Vapor Processing Systems

Thermal Gradient Tensile Creep Rupture Testing of Advanced Turbine Environmental Barrier Coating SiC/SiC CMCs

- Advanced high stability turbine vane environmental barrier coatings demonstrated based turbine environmental barrier coatings being successfully tested for long-term creep rupture capability
- The new generation bond coat tested up to 2500F showed no major degradations
- The new CVI-MI with Hi-Nicalon™ Type S Type S fibers SiC/SiC CMCs also showed promise in creep resistance



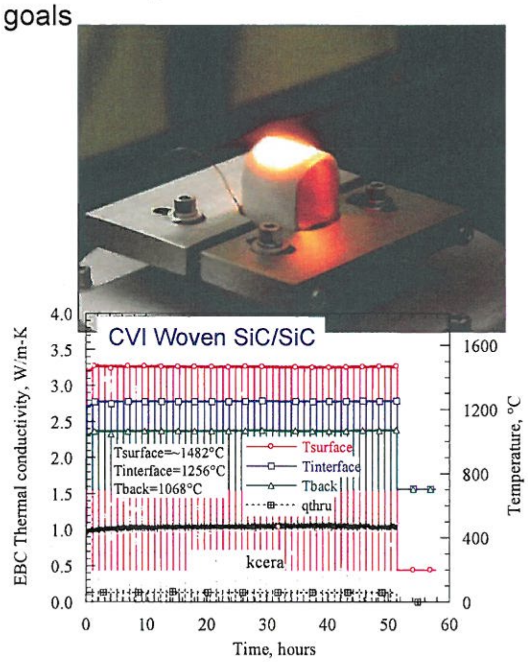


Modeling is in progress

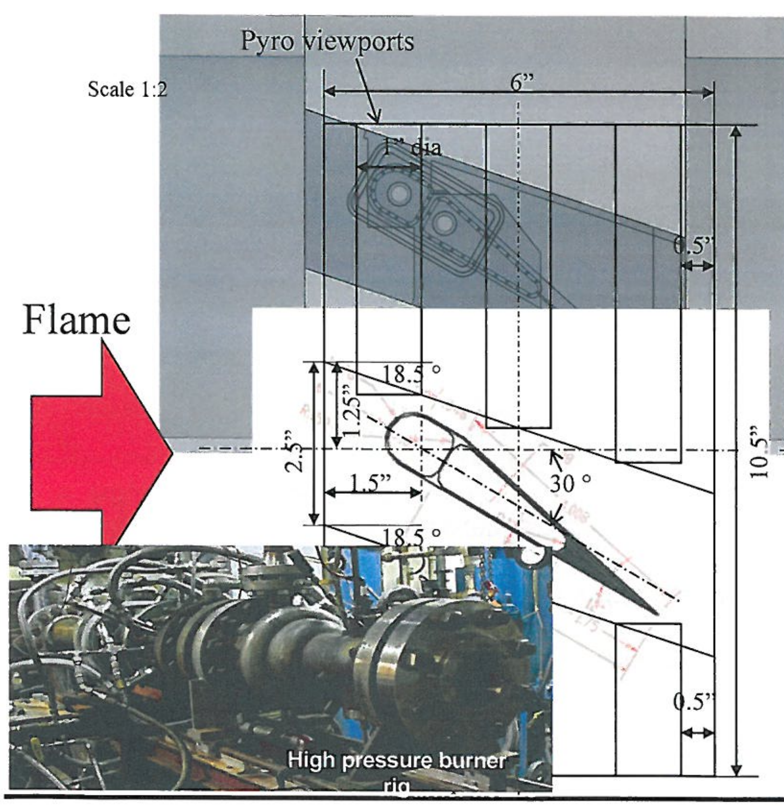
NASA Turbine Environmental Barrier Coating Testing Developments

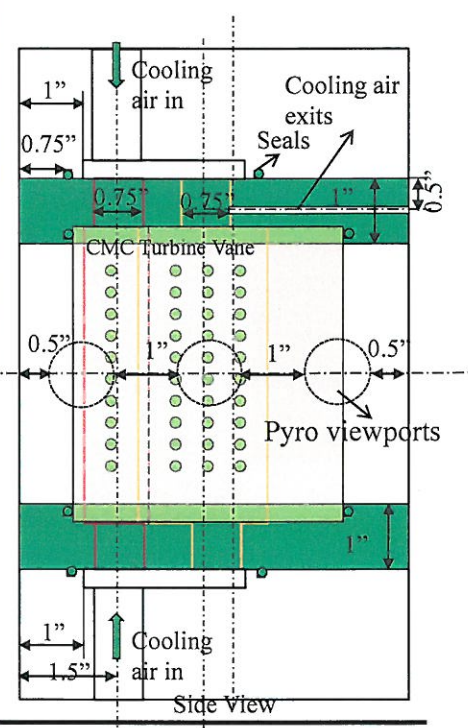
- Advanced EBC top coats tested in coupons under laser heat flux cyclic rigs up 1700°C
- Coated subelements coating tested up 1500C under laser thermal gradient for 200 hr
- EBC systems show high stability in High Pressure Burner Rig Tests
- Thermal conductivity of 1.2 W/m-K met program goals

High pressure burner rig, 16 atm, 31 hr



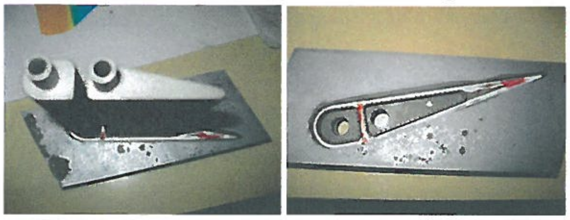
Advanced High Pressure Burner Rig Testing for Turbine Vanes

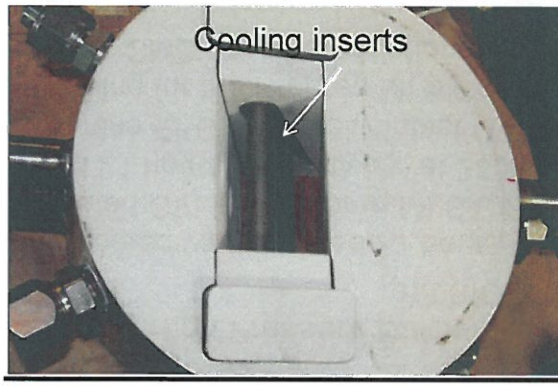


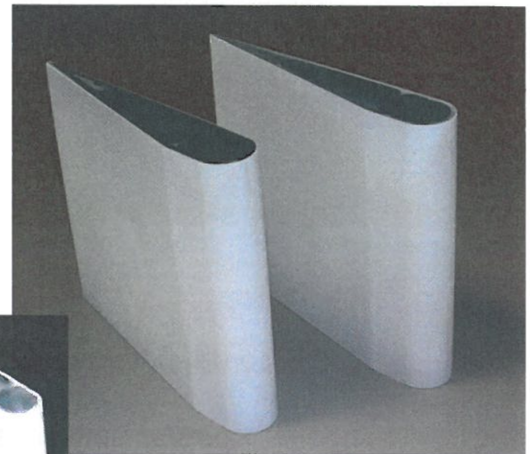


Advanced High Pressure Burner Rig Testing for Turbine Vanes

- High Pressure Burner Rig test sections manufactured
- Nickel base superalloys and thermal barrier coatings used inner sections
- Total 6 SiC/SiC vanes coated
- 2 uncoated SiC/SiC turbine vanes tested at 2400F
- 2 coated SiC/SiC turbine vanes tested at 2500F
- 1 film-cooled vane under testing at 2600F

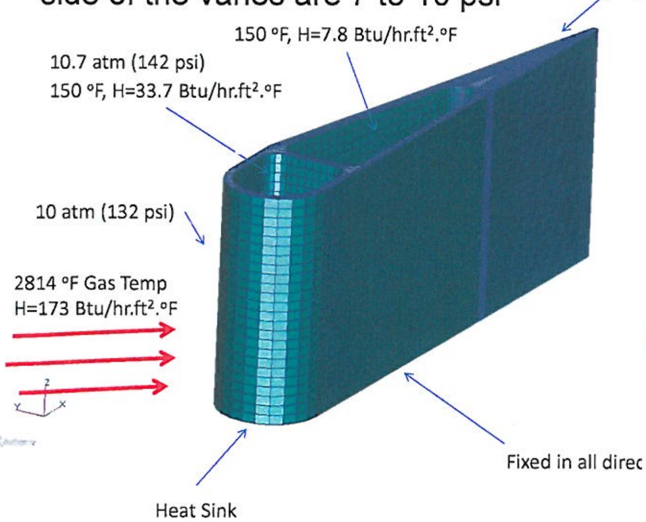


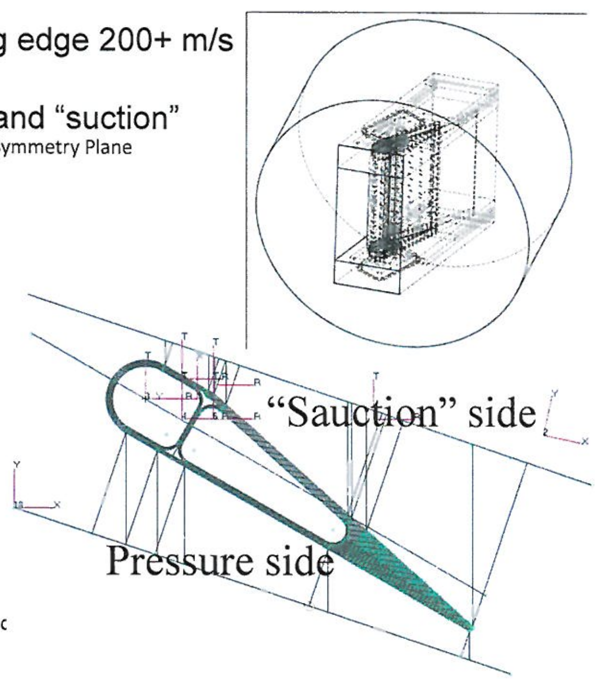




General Test Conditions

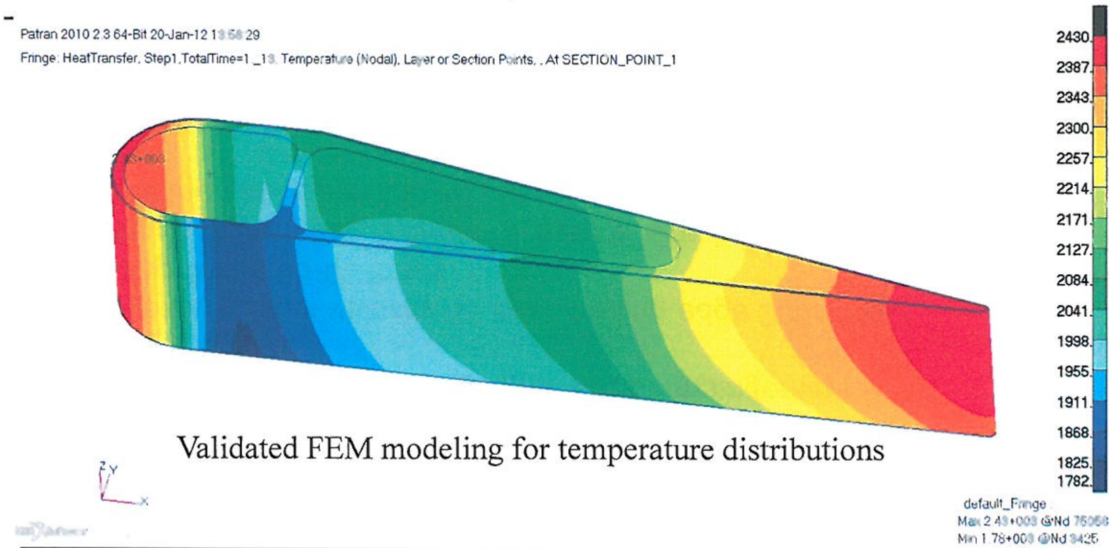
- Fuel to air ratio F/A 0.045, mas air flow 1.5 lbm/s, pressure 10 atm, internal impingement or impingement + film cooling
- Inlet leading edge velocity 65 m/s, trailing edge 200+ m/s
- Cooling flow 0.05-01 lbm/s
- Pressure differential between "pressure" and "suction" side of the vanes are 7 to 10 psi





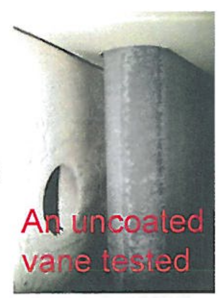
General Test Conditions - Continued

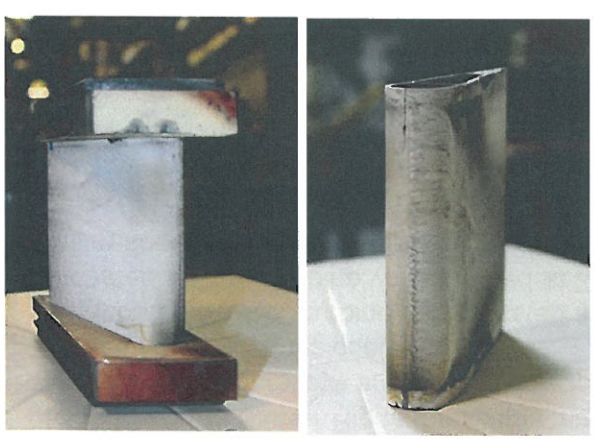
- Fuel to air ratio F/A 0.045, mas air flow 1.5 lbm/s, pressure 10 atm (132psig), internal impingement or impingement + film cooling at up to 10.7 atm (142 psig)
- Inlet leading edge velocity 65 m/s, trailing edge 200+ m/s
- Cooling flow 0.05-0.10 lbm/s
- Pressure differential between “pressure” and “suction”



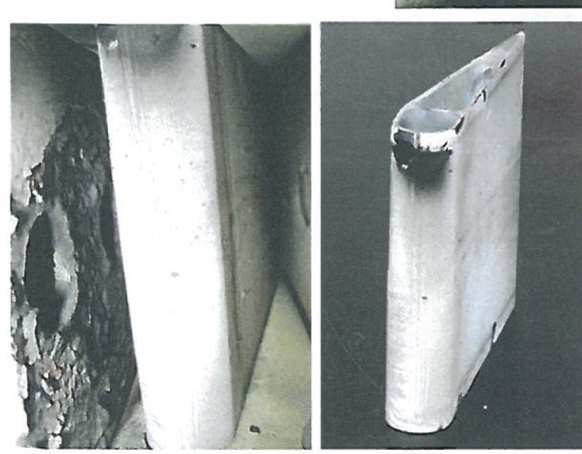
High Pressure Burner Rig Testing for Validating EBC Coating and SiC/SiC Vane Components

- Uncoated vanes tested 21 hours
- Coated CVI and Prepreg MI SiC/SiC vane successfully tested 31 and 21 hours respectively, at 2500 F+, reaching TRL of 5
- Turbine EBCs generally intact (some minor partial coating top coat spalling for the Prepreg MI SiC/SiC vane)
- Minor CMC vane degradations after the testing





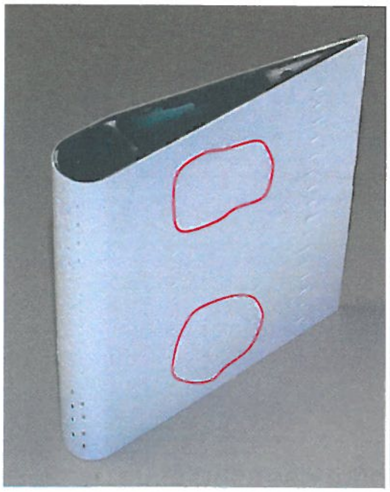
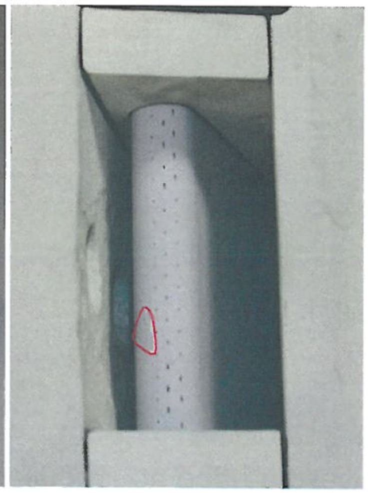
Coated CVI vane after 31 hour testing at 2500°F+ coating temperature



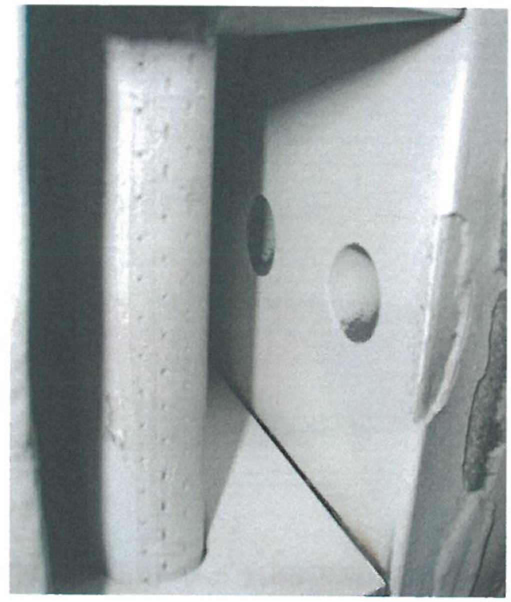
Coated Prepreg vane after 21 hour testing at 2500°F+ coating temperature

High Pressure Burner Rig Testing for Validating EBC Coating and SiC/SiC Vane Components - continued

- A first coated Prepreg MI film-cooled SiC/SiC vane in testing at 2600F+ at 10 atm, with film cooling air flow 0.05 lbm/s
- Some initial coating defects
- Accumulated 8 hours in the high pressure burner rig rig

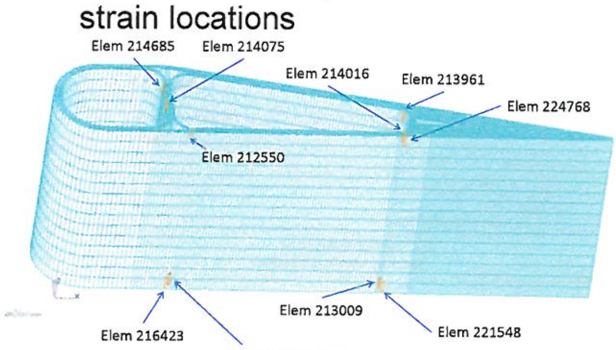



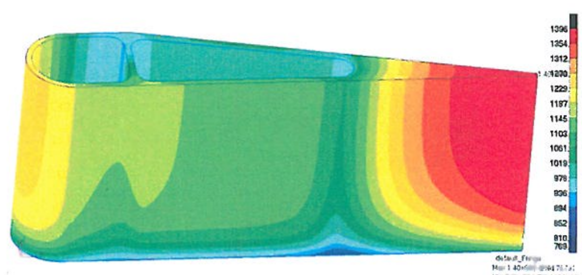
The vane had some initial defective environmental barrier coatings



High Pressure Burner Rig Testing and FEM Modeling - Creep

- Preliminary transient and creep models for the impingement vane established
- Accelerated creep for uncoated vane can resulted in vane failure in high creep strain locations



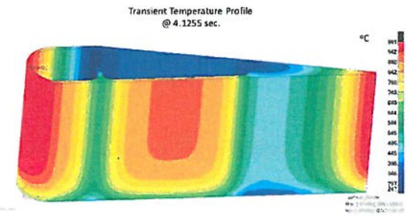


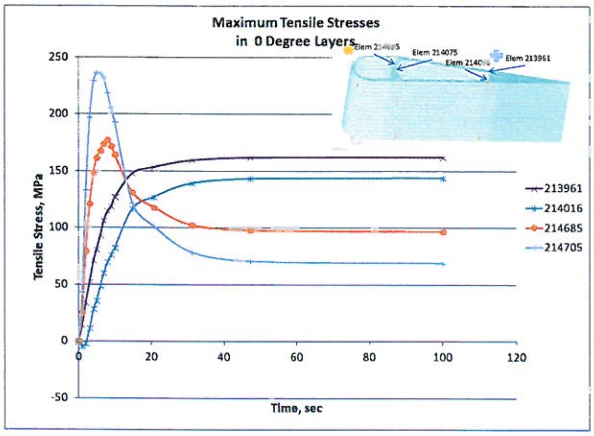
Critical elements likely to fail in creep and transient thermal loading

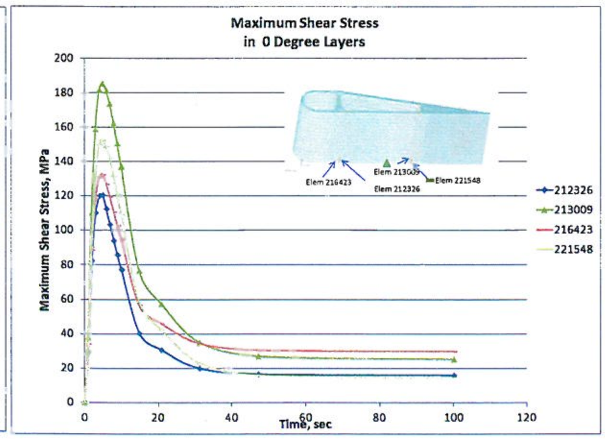
Creep strains estimated at 1500hr

High Pressure Burner Rig Testing and FEM Modeling – Thermal Transients

– Transient stress modeling for 0 degree plies



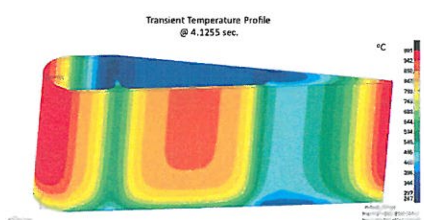


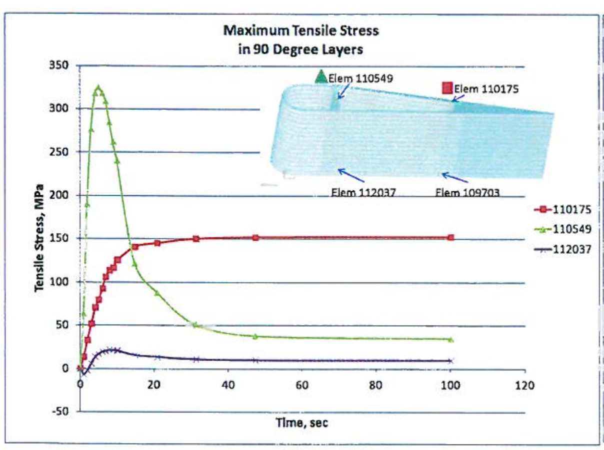


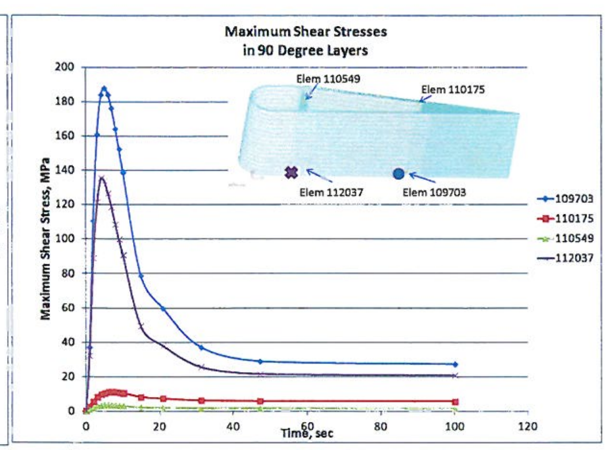
National Aeronautics and Space Administration

High Pressure Burner Rig Testing and FEM Modeling – Thermal Transients - continued

– Transient stress modeling for 90 degree plies







Summary

- Vapor deposition turbine EBCs developed with some confidence for complex large vane components
- An ERA turbine coating downselected and showed high stability and long-term durability on state of the art SiC/SiC CMCs
- The vapor based EBC processing approaches demonstrated vane EBC composition realization, acceptable coating surface roughness and thickness controls
- Multiple advanced turbine environmental barrier coating coated SiC/SiC CMC vanes tested in engine relevant rig combustion environments, showing component viability and initial durability, demonstrating TRL of 5 under the NASA ERA program

Conclusions

- The EBC developments have major advances for turbine airfoil applications in composition and processing with durability and performance
- Realistic impingement and film cooled vane component testing can be achieved in the High Pressure Burner Rig environments
- Turbine EBCs can help improve the turbine durability in the harsh engine environments, addressing key HPT turbine airfoil development issues, in particular, thermal stress resistance and environment related degradations in complex transient cyclic loading, creep and harsh combustion environments
- Coating process control for large airfoil components still need improvements

Future Plans

- Film-cooled vane(s) continued to be tested
- Next generation environmental barrier coating systems also being incorporated
- CFD models for full 3D vane high pressure burner rig testing in progress
- Continued vane subelement testing for EBC-CMC cyclic durability improvements and model developments